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Liquid-Liquid Dispersion: Effects of Dispersed Phase Viscosity on Mean Drop Size and Distribution in Stirred Vessel

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Abstract

Drop size distributions in liquid-liquid dispersion are essential in industrial processes as it involve mass and heat transfer between the phases. An experimental investigation was conducted to study liquid-liquid dispersion in stirred vessel. The objective of this experiment is to study the effects of dispersed phase viscosity (moderate to high) on the mean drop size, d_{32} and drop size distributions at different impeller speed. Different grades of silicone oils were used to create oil in water dispersions with surfactant stabilization and by using Rushton turbine as impeller. Laser diffraction technique (Malvern Mastersizer 2000) was used to measure the mean drop size and distributions. Results showed that mean drop size, d_{32} are affected by dispersed phase viscosity especially at high dispersed phase viscosity. At low viscosity, higher uniformity of drop sizes was produced as higher drop size distribution curve was obtained and the curve shifted to the left of the graph when the impeller speed was increased. Higher viscosity exhibit larger change in d_{32} as the impeller speed increase (92.76%) compared to low viscosity (44.03%) which is caused by different breakage mechanism.

Keywords: Liquid-liquid dispersion; Viscosity; Impeller speed; Laser diffraction; Mean drop size.

Introduction

The dispersion of immiscible liquids is often encountered in many industrial processes such as extraction, suspension polymerization and multiphase reactions [1]. The drop size distributions in the dispersion are related to the interfacial area which governs the amount heat and mass transfer between the phases. Therefore, knowing the interfacial area in the dispersion is an important factor to determine important parameters such as interphase reaction rate and transfer rate. To predict the interfacial area in the dispersion, it is important to study and understand the underlying principles behind the drop formation[2] .

Dispersion process involves simultaneous process of drop breakup and drop coalescence. Drop breakup is caused by external forces such as turbulent pressure fluctuations and viscous stress while resisted by surface force [3]. For drops with high viscosity, it is also stabilized by internal viscous force. Drop coalescence on the other hand occurs when drops collide together and combined into bigger drops. This process involves drainage and rupture of the intervening liquid film between the drops which is governed by the physical properties of the fluids [4]. The dynamic equilibrium between drop breakup and drop coalescence will determine the drop size distribution in dispersion. To describe it in mathematical model, population balance equation can be used.

The mean drop size and distributions are influenced by the operating parameters of the dispersion process and the properties of the liquids which include viscosity and density [5].

Earlier studies on drop size distribution in stirred vessel are often conducted for dilute and low dispersed phase viscosity or inviscid system. In such system, the internal viscous force are dominated by surface force for drops stabilization, therefore it can be neglected. The effect of viscosity is then introduced in modelling of drop size by Kolmogrov and Hinze [1].

Most studies focused on dilute and inviscid system which is limited to narrow range applications and few studies were conducted at high dispersed phase viscosity. Available works on how dispersed phase viscosity influenced the equilibrium mean drop size and drop size distributions were conducted in surfactant free system by Calabrese [6], Podgorska [1] and in surfactant stabilized system by [7].

The aim of this work is to investigate the effects of dispersed phase viscosity (moderate to high) on mean drop size and distributions for moderate dispersed phase fraction (ϕ=0.1). Instead of focusing only on the mean drop size, this paper also discusses the drop size distributions of the dispersions which enable better discrimination of prediction models. This work focused on the occurrence of drop breakup only by adding surfactants into the system.

Experimental

Experiments were conducted in clear cylindrical flat bottom stirred tank with internal diameter of T=0.20m equipped with four identical baffles with width equal to T/10 each. The tank was filled with distilled water as continuous phase to a height of H=T. Standard six-blade stainless steel Rushton turbine with diameter D=0.08m was used at bottom clearance equal to T/3. Lighting was provided by four fluorescent lights at the corners of the vessel to observe the dispersion process. Various grades of silicone oils (20, 350 and 500 mPas) supplied by Sigma Aldrich were used as dispersed phase. The properties of the oils were tabulated in Table. An amount of 0.3% (by weight) of Sodium dodecyl sulphate was dilute into the distilled water before adding the oil. By using a syringe, required amount of silicone oil (equivalent to φ=0.1) were added into the distilled water near the impeller region. The dispersion process were performed at five different impeller speeds (300, 350, 400, 450 and 500 rpm) which are in the range of 33 000 < Re < 55 000. The minimum impeller speed is above the minimum speed required for complete dispersion and the maximum speed is chosen below the speed where air entrainment start to occur in the vessel.

Sampling was carried out after 60 min of the mixing process. Samples of 50ml of the suspension were collected at a fixed position near the impeller region where the rate of drop breakage is high. The sample is taken to a Malvern Mastersizer 2000 for drop size measurement process. The laser diffraction equipment is well known and widely used in this area [8],[7], [9], [10], [11]. It capable of measuring drops in the range of 0.02 – 2000μm with an accuracy of $\pm$ 1%. The equipment requires the information on the refractive index of the dispersed phase (see Table 1). From the measurement, for all dispersion, drop size distribution curves and Sauter mean diameter, d_{32} were produced and determined.

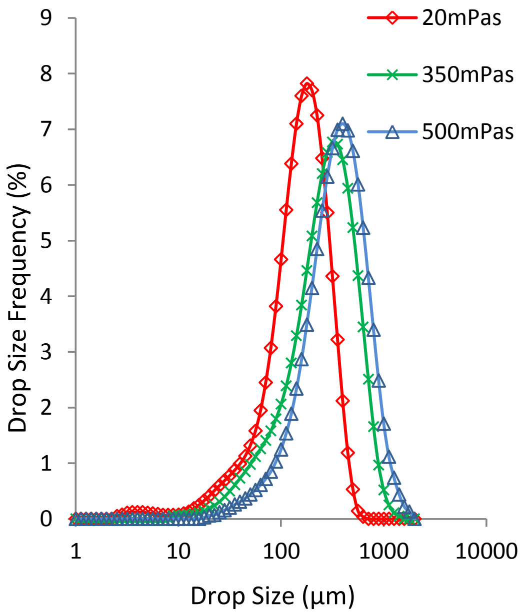
Table 1: Properties of various grades silicone oils

Types of Oil	Viscosity, mPa.s	Density, kg/m^3	Refractive Index
Silicone Oil 20	25	1001.00	1.39
Silicone Oil 350	350	968.00	1.403
Silicone Oil 500	500	970.00	1.403

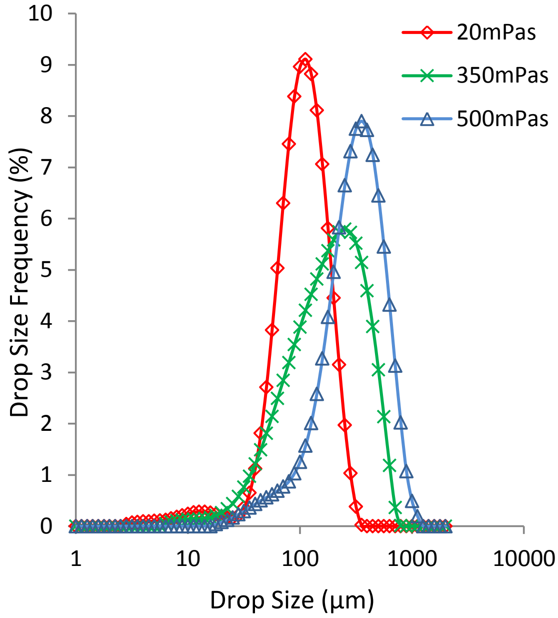
Result and Discussions

Effect of Dispersed Phase Viscosity on Drop Size Distribution

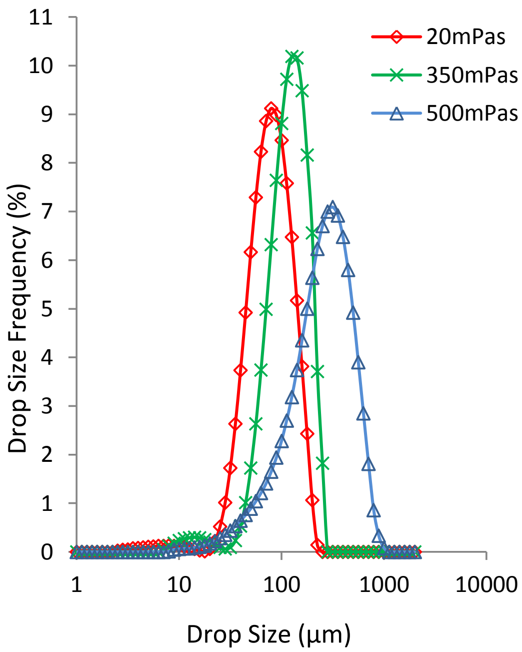
The drop size distribution curves obtained for different dispersed phase viscosity and at different impeller speed is presented in Figure 1(a) to (e). The curves show the range of drop sizes in the dispersion. The figure shows that as the dispersed phase viscosity increase, the curves shifted to the right where the sizes of the drops are higher. In most cases, the distribution curves for 25mPas are much taller compared to 350 and 500mPas which shows that the drop sizes at low viscosity are more uniform. The drop size distribution also broadens as the viscosity is increase above 25mPas. It means that low dispersed phase viscosity produce dispersion with smaller drops compared to high dispersed phase viscosity. Similar observations were reported by [1] and [7]. Therefore, larger surface area is expected at low viscosity.



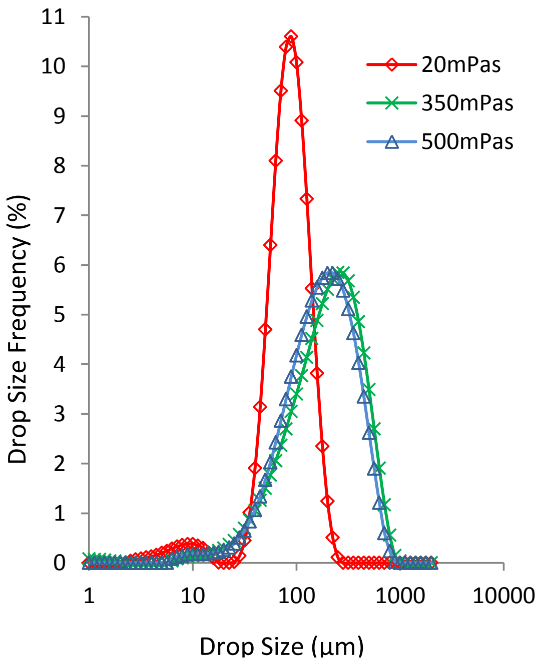
(a) 300rpm



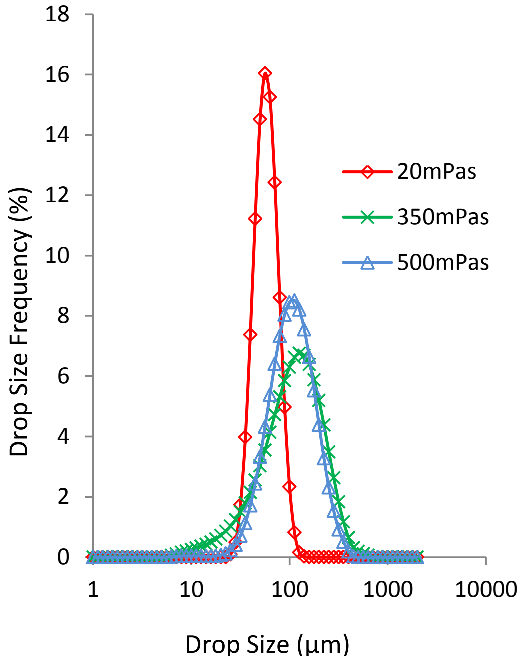
(b) 350rpm



(c) 400rpm



(d) 450rpm



(e) 500rpm

Figure 1 (a) – (e): Drop size distribution curves for different dispersed phase viscosity at different impeller speed

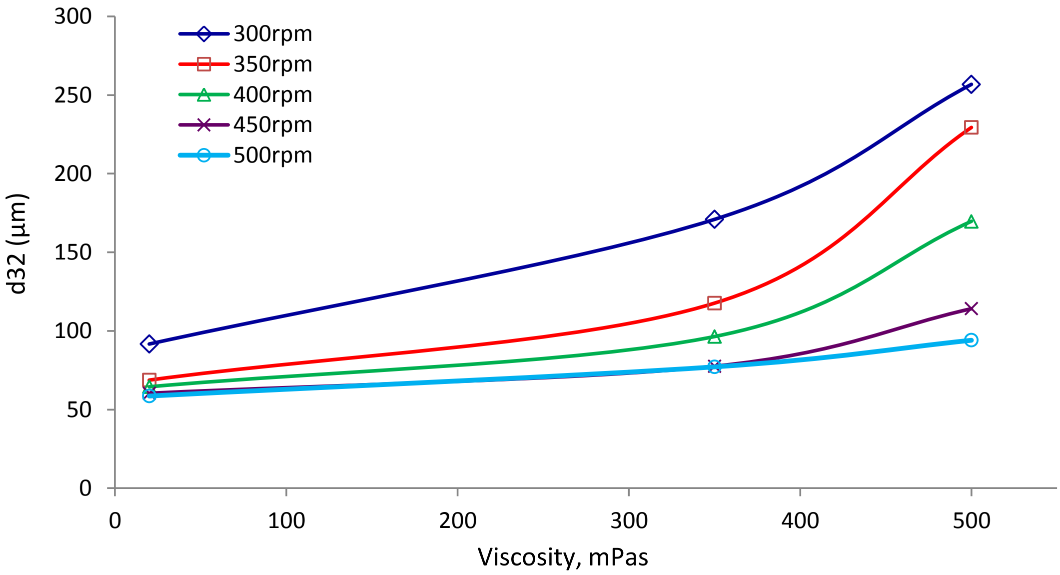


Figure 2: Graph d_{32} versus dispersed phase viscosity at different impeller speed

Effect of Dispersed Phase Viscosity on Sauter Mean Diameter

The Sauter mean diameters, d_{32} obtained from the dispersion are plotted against the dispersed phase viscosity for different impeller speed as shown in Figure 2. Increasing trends of d_{32} are observed from the figure for all impeller speeds. The value of d_{32} increases as the dispersed phase viscosity increase from 20mPas to 500mPas. It shows that dispersed phase viscosity does have an effect on the equilibrium mean drop size by contributing in the stability of the drops to resist drop breakup (put ref). The behaviour can be explained by drop breakage mechanism where drop breakage is resisted by cohesive forces. In this study, since the silicone oils have similar interfacial tension with water, the change in d_{32} is caused by the viscosity different only. The viscous force of the drops helps to stabilize the drops towards breakup by giving additional cohesive force, causing less drop breakup [12]. Drops with higher viscosity also have lower drop breakage probability where the breakage events area in the stirred vessel are smaller compared to low viscosity due to the stability of the oil. The breakage event in stirred vessel was observed using CFD by [2].

From Figure 2, by comparing the change of d_{32} for 20, 350 and 500mPas according to impeller speed, one can see that higher viscosity experienced bigger change in d_{32} as the impeller speed increase although their d_{32} is still bigger compared to low viscosity. From 300 to 500rpm, the d_{32} change for 500, 350 and 20mPas are 92.76%, 75.61% and 44.03% respectively. This is because smaller drops tend to be more stable compared to bigger drops.

Conclusion

Experimental investigation has been conducted to study the effect of dispersed phase viscosity on drop mixing at different impeller speed. From the analysis, it can be seen that at viscous force does have an effect on the drop size distribution and mean drop size by affecting the rate of drop breakage. At high viscosity, drops are more stable and the possibility to deform is smaller. From the drop size distribution curves, low viscosity dispersed phase produced narrower distribution where the drops sizes are more uniform.

Therefore, smaller d_{32} was achieved leading to higher surface area. At different impeller speed, higher viscosity exhibit bigger changes in d_{32} although the d_{32} still larger compared to low viscosity dispersed phase. It shows that at different viscosity, the breakage mechanism of the drops is different.

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